

ESPC Coupled Global Prediction System

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Award Number: N0001415WX00818
<http://www.7320.nrlssc.navy.mil>

Award Number: N0001415WX00656
<http://www.nrlmry.navy.mil>

LONG-TERM GOALS

Develop and implement a fully coupled global atmosphere/wave/ocean/land/ice prediction system capable of providing daily predictions out to 10 days and weekly predictions out to 30-90 days. Initial Operational Capability is targeted as 2018. Predictions will provide environmental information to meet Navy and DoD operations and planning needs throughout the globe from undersea to the upper atmosphere and from the tropics to the poles. The system will be implemented on Navy operational computer systems, and the necessary processing infrastructure will be put in place to provide products for Navy fleet user consumption.

OBJECTIVES

Develop and implement a coupling infrastructure and interoperability layer to enable the component models to exchange information needed to make global earth system predictions. For each of the component models, develop and test coupled physical parameterizations and emphasize testing of new feedback loops that arise in the coupled system. Implement the tripolar grid for WaveWatch-III and wave forcing in the ocean. Incorporate time-dependent, radiatively active, and cloud-nucleating aerosols into NAVGEM for use in long-term simulations and forecasts and for use in the full coupled system.

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APPROACH

There are five tracks for this project. Key performers for coupling infrastructure and interoperability layer extensions are Timothy Whitcomb (NRLMRY), Alan Wallcraft (NRLSSC), and James Chen (SAIC). Oceanography and meteorology leads for coupled physical parameterizations for NAVGEM/HYCOM are James Richman (NRLSSC) and James Ridout (NRLMRY). Key performers for coupled physical parameterizations for NAVGEM/CICE/HYCOM are Pamela Posey (NRLSSC), Shouping Wang (NRLMRY), and Neil Barton (NRLMRY). Key performers for coupled physical parameterizations for NAVGEM/WaveWatch-III/HYCOM are Erick Rogers (NRLSSC), Alan Wallcraft (NRLSSC), Yalin Fan (ASEE/NRLSSC), and Dan Moore (Imperial College). Key aerosol physics performers are Ming Liu (NRLMRY) and Douglas Westphal (NRLMRY)

A necessary first step in the development of a coupled modeling system is the establishment of a coupling infrastructure. We use the Earth System Modeling Framework (ESMF) library as the foundation, and use additional capabilities from the “NUOPC Layer” (based on coordination work in the National Unified Operational Prediction Capability) that provides a set of conventions and shared routines to manage the model and coupler components, march model components in terms of the coupling time scale, conduct automated compatibility checking to ensure matched import/export fields, and to provide a platform to easily develop customized couplers. The synergistic development of the NUOPC layer and ESPC has allowed the NUOPC layer developers to respond to needs identified by ESPC and leverage ESPC as a testbed for NUOPC developments. The design strategy for ESPC is to limit the impact to the existing NAVGEM, HYCOM, and CICE forecast model systems’ code structure and code flow as much as possible. This allows us to maintain agility while the component models are under development, and avoids additional errors due to extensive refactoring.

The Navy atmospheric forecast system (NAVGEM) and ocean-sea ice forecast system (HYCOM/CICE) have never been coupled at high resolution. The coupled processes will be incrementally tested by examining each step of the feedback loops. A range of physical processes will be included and excluded to ensure proper interactions between these processes. Both short term (10 day) and long term (30 day) tests will be conducted for this work. We will perform tests on NAVGEM and HYCOM in uncoupled, loosely coupled, and two-way coupled modes. The approach for FY14 has been testing different mixing and convection schemes in uncoupled NAVGEM (to address excessive cyclogenesis in extended runs that was identified earlier) and limited testing of the coupled NAVGEM/HYCOM system for the MJO events during the DYNAMO experiment in November, 2011. Initial experiments will occur with each component using its own flux computation which will lead to non-conservation and other undesirable effects. Addressing these issues will require implementation of alternate parameterizations and flux estimates in a new cycle of tests. In addition, the coupled system permits testing additional physical processes at the interface (such as sea-spray effect, dissipative heating, frictional velocity, and surface roughness) and accounting for momentum stress using shear of winds and currents across the interface.

The sea-ice component of this project requires modification of CICE versions 4 and 5 to run in the coupled ESPC global model with NUOPC tools, NCODA routines for sea ice concentration assimilation in the global coupled system, and the coupling algorithm for passing variables from CICE to NAVGEM. Summer seasonal forecasts (out to 5 months) have been run as part of the Study of the Environmental ARctic CHange (SEARCH) Sea Ice Outlook (SIO) effort, which is now managed as part of the Sea Ice Prediction Network (SIPN): these forecasts will be repeated with the fully coupled model.

Coupling the wave model requires integrating wave forcing from WaveWatch III into the ocean model as well as ensuring physical consistency of momentum budgets as atmosphere/ocean fluxes pass through the intermediate wave layer. Initial efforts of coupling wave forcing into HYCOM met with computational challenges. To mitigate the expense, Stokes drift is processed as a vertical profile that's integrated across fixed finite volume layers instead of sampled at fixed depths. New tests will also use a modified mixed layer parameterization (KPP instead of Mellor-Yamada). To ensure consistency with the ocean model, a global tri-pole grid will be implemented in WW3, which requires accounting for an "Arctic seam" in the spatial propagation of wave energy. To allow for higher spatial resolution while maintaining scalability, we will test the proposed "hyper-scaling" (H. Tolman, poster presentation at Waves in Shallow Environments conference, April 2013) technique. Two-way coupled WW3 will be implemented into operational Global Ocean Forecasting System (GOFS) 3.5, thus making it the coupled HYCOM / CICE / WW3 component of ESPC. In addition to the wave-ocean coupling, ice coverage will be imported to WW3 from CICE.

We will incorporate time-dependent, radiatively active, and cloud-nucleating aerosols into NAVGEM for use in long-term simulations and forecasts for ESPC applications. We are relying on approaches, findings, lessons-learned from the NAAPS and COAMPS aerosol implementations. As in NAAPS, we will include the Navy-relevant species of dust, smoke, sea salt, SO₂ and sulfate. We utilize a library of microphysical parameterizations and source inventories and allow for run-time control of microphysical processes, radiative processes, and cloud-interactions.

WORK COMPLETED

Technical Upgrades: Many technical upgrades have been made to the coupled system software. These include 1) updating ESPC to be ESMF version 7 compatible, 2) implemented a more efficient (off-line) calculation of regrid weights, 3) improved efficiency of transferring fields between HYCOM/CICE and NAVGEM with the NUOPC layer, 4) incorporated new versions of NAVGEM (CV1.01), HYCOM (2.2.99i_relo), and CICEv4 (2.2.99i_relo) into the ESPC standard version, 5) implemented the capability to use NAVGEM's thin grid within the ESPC system, 6) addition of shared calendar tools, and 7) resolved ESPC reproducibility issues. In addition, many issues have been explored, including 1) implementation of an implicit scheme, 2) improved load balance and performance issues, 3) possible implementation of different coupling timesteps between component models, implementation of WWIII. Wiki-based bug reporting systems have also been implemented.

Parameterization Improvements: Changes were made in the COARE 3.0 air-sea flux parameterization in HYCOM in the coupled system, in part updating the physics to include imported surface pressure data from NAVGEM. Surface pressure data have not historically been part of the data stream provided for HYCOM operational forcing (where a constant value was used), and is needed to compute saturation mixing ratios. In NAVGEM, a correction was made to the implementation of the HYCOM COARE 3.0 air-sea flux scheme involving its integration with the fully implicit computation of vertical mixing. Also, after additional development during the year under the ONR 6.1 Unified Physics DRI and NRL 6.2 MJO projects, including an improved representation of the coupling of convection with turbulent plumes, the modified Kain-Fritsch convection scheme was implemented under configuration management in the coupled system for a broader range of tests. An updated version of this scheme was under preparation at the close of the FY for a planned upgrade in FY16. The upgrade will, in part, incorporate changes based on results from an international MJO intercomparison study.

System testing expanded in FY15. In addition to our DYNAMO focus period in the fall of 2011, testing with the new physics included two multi-month integrations with start dates in 2014. The first integration began on 31 March, 2014, and extended through the end of September. The second integration began on 1 October, 2014, and extended through the end of February 2015.

Wave Modeling: WAVEWATCH III (WW3) has been adapted by NRL to handle computations on a tripole grid for calculation of gradients in input fields (e.g. bathymetry, currents) and for propagation using the model's first order scheme. The primary challenge is to allow computations near and across the "Arctic Seam" which stitches the grid rows (with dissimilar grid indices) together at high latitudes. The new functionality is verified, and will allow WW3 and HYCOM to both be applied on tripole grids together, reducing grid transformation errors during coupling. In FY15, this new feature has been applied to full-scale simulations on the DSRC (see Results section).

We determined that the benefit of running both models on tripole grids does not outweigh the general unsuitability (in terms of computational efficiency) of the tripole grid for wave model use. Therefore, we decided not to implement the tripole grid for 2nd or 3rd order propagation schemes, but instead developed and demonstrated more efficient global grid configurations for WW3 which will eventually form the basis of the ESPC wave model, replacing the tripole WW3. These new configurations are based on three-grid computations (with inline boundary communication via WW3's multi-grid capability), two polar stereographic grids for high latitudes, and a single regular grid for low latitudes. Two examples are added to the NRL SVN code repository.

Work is ongoing to integrate Stokes drift from WW3 into HYCOM. Since the ESMF/NUPOC coupling infrastructure for WW3 is nearly complete but still under construction, this WW3 to HYCOM coupling is being done through files. The necessary grid computations and modifications to governing equations of HYCOM have been made, and have been tested for 1D (Ocean Station Papa), 2D (idealized sloping beach), and 3D (Hurricane Ivan). In all three, results are stable and qualitatively sensible. Comparisons to observations have been made for the 1D case, with significant improvement. Comparisons to observations for 2D and 3D cases are not yet done. There are issues with noise at the open boundary in the 3D case which must be addressed. A detailed report is being prepared by Dan Moore and Alan Wallcraft to document this progress.

Aerosols: We continue to focus on the numerical properties of aerosol modeling in computational efficiency, mass conservation and being positive definite as the transport of aerosol species are highly depending on the accuracy of numerical transport algorithms. Adapted from WRF, a Semi-Lagrangian advection scheme is being implemented in the vertical in NAVGEM to process the gravitational sedimentation of aerosol particles. It allows the use of a much large time step to advect particles across a large distance in one step. This approach is to replace the conventional costly Eulerian finite-difference advection in which a linear time-splitting is used to advect particles in multiple small-time steps to precede particle falling repetitively within one large time step. Therefore, the new Semi-Lagrangian advection significantly increases the computational efficiency of aerosol modeling and makes the modeling of multiple aerosol species possible in the next stage of NAVGEM aerosol model development. This SL algorithm also matches the SL dynamics core of NAVGEM that is increasing the time steps as the grid resolution increases from T425L60 to T681L80.

We are testing the sedimentation code of aerosol species by calculating mass fluxes in every pressure grid level to examine the means, maximums, minimums of fluxes. That is to evaluate how well the new sedimentation performs on vertical transport of aerosol particles. We are currently doing detailed

mass flux examination. The application of SL advection in aerosols will be further extended to the use of multi-cloud species microphysics in NAVGEM that contains precipitable species (rain, snow, graupel, and hail) to provide the important mechanism for aerosol particle wet deposition and aerosol condensation enucleation in cloud modification. Particles can descend across over one and more grid layers in the vertical each timestep, depending on settling velocities that are functions of density, size and air mass dynamics. The implementation work includes general tests on numerical stability and diffusion, and conservation as well. Note that SL advection is popularly used in the sedimentation of cloud species, especially in the WRF research-community model for all cloud microphysics modules.

We have started to develop the precipitation removing process in NAVGEM. There are two separated wet removals by (1) convective precipitation and (2) large-scale precipitation. Since the standard-version cloud (n2p) in NAVGEM is a highly simplified microphysics, it does not resolve any precipitable species of rain, snow/graupel, and does not calculate any vertical transport of clouds, e.g. no cloud sedimentation and no vertical advection by large-scale sinking/lifting. Hence the cloud mass fluxes of rain, ice, snow/graupel at every grid point have to be somehow diagnostically estimated as rainfall and snowfall rates. These rates will be used to calculate scavenging rates.

Meanwhile, we are developing the code to calculate the tendency and budget of aerosol mass in transport and physics processes. This is to monitor to the conservation property of mass in advection, mixing, and individual physics processes through the mass changes of aerosol integration in space and time, driven by the NAVGEM dynamics.

RESULTS

Diagnostic analyses of ocean currents in the coupled system included simulations of surface drifter trajectories, as well as ongoing work comparing surface velocities with buoy observations (collaborative effort through NRL 6.2 MJO). Comparisons of simulated drifter trajectories during DYNAMO with observations showed that results based on coupled system hindcasts were only slightly worse than those obtained using an ocean-only analysis. Hindcast tests showed that improvements to the MJO simulation for the DYNAMO period improved zonal equatorial winds, in particular those associated with the westerly wind burst following the second MJO of November 2011. The increased surface stress associated with the westerly wind burst acts to boost the Indian equatorial countercurrent, which in turn impacts air-sea fluxes in both NAVGEM and HYCOM (Fig. 1, left panel). Computed feedbacks appear to be nonnegligible, with, for example, perturbations to the surface latent heat flux of up to 10 W m^{-2} (Fig. 1, right panel).

The DYNAMO period MJO hindcast case study continued, and tests with physics updates showed promise of MJO predictability out to ~40 days in the Indo-West Pacific region (Fig. 2). The multi-month integrations, however, served to highlight the need for some additional work. Results show some issues with double ITCZ formation, for example, a deficiency shared to varying degrees by all of the CMIP 5 models (Oueslati and Bellon 2015). In addition, regions of excessive heating developed along the equator, a feature particularly evident during the summer of 2014. These results are perhaps not too surprising, considering reports of false El Niño predictions by other coupled systems for the period. Nonetheless, efforts were initiated to better understand and resolve related deficiencies in the coupled system.

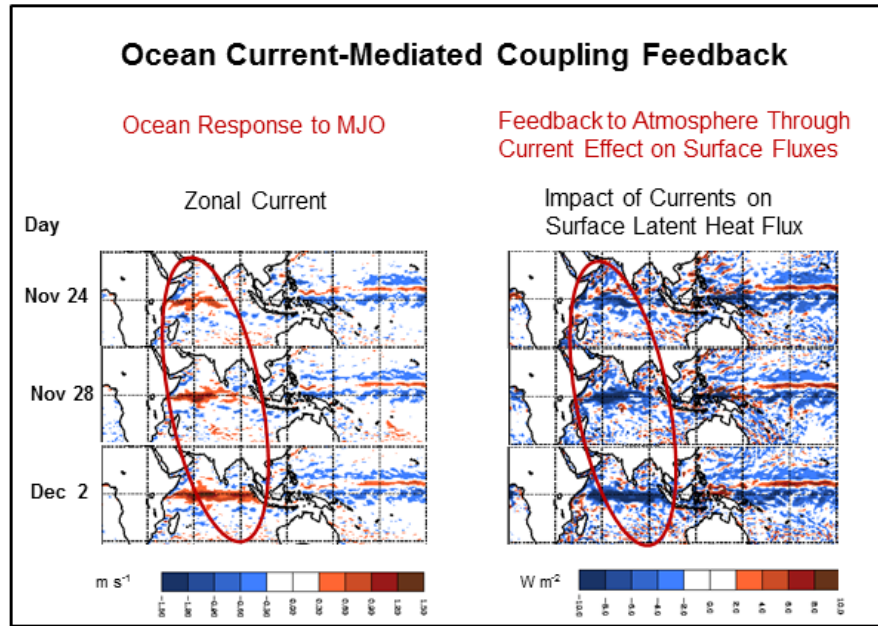


Fig. 1: (left panel) Ocean zonal surface current (m s^{-1}) for three days (daily means) during the second MJO event of the DYNAMO observational period from a NAVGEM-HYCOM-CICE forecast started at 00Z 1 NOV 2011. (right panel) Diagnosed impact (W m^{-2}) of the ocean current on the surface latent heat flux.

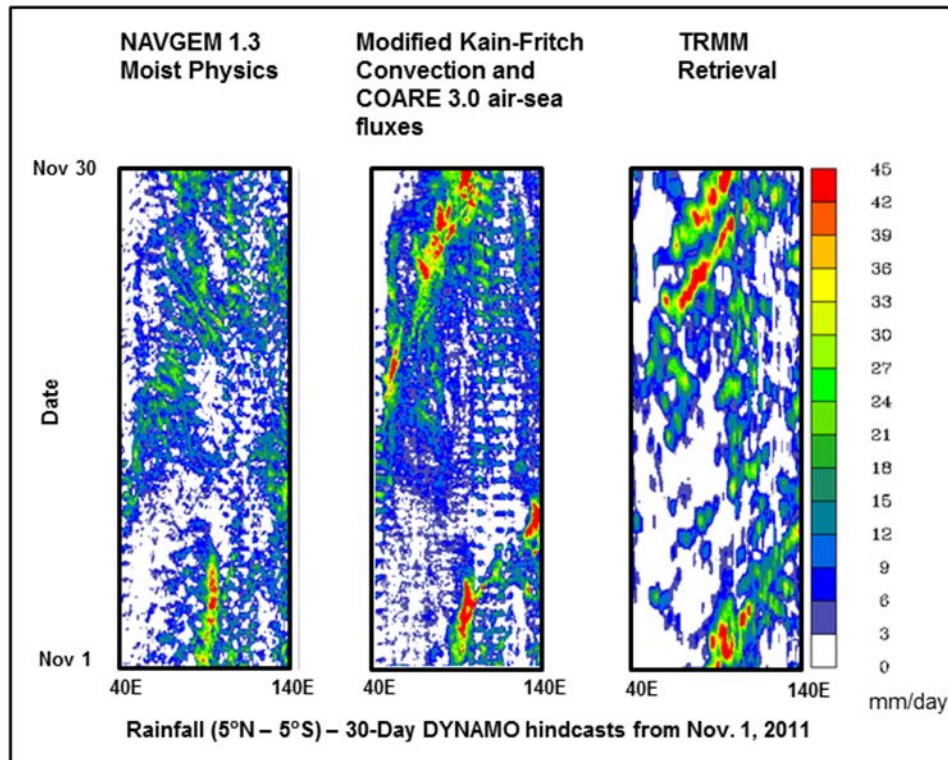


Fig. 2: Rainfall (mm day^{-1}) averaged from 5S-5N for 30-day NAVGEM-HYCOM-CICE forecasts started at 00Z 1 NOV 2011 with control NAVGEM physics (left panel), and improved NAVGEM physics (center panel), compared with TRMM observations (right panel).

Coupling NAVGEM to CICE5 is able to mitigate substantial biases in low-level temperature in NAVGEM forecasts. Fig. 3 shows the 120-h forecast biases of NAVGEM 2-m temperature as compared with ECMWF analyses during May 2014. Both the warm bias in the Arctic and the cold bias in the Antarctic are substantially reduced through coupling to CICE5. Additional experiments indicate that much of this improvement comes through an improvement to the sea ice albedo.

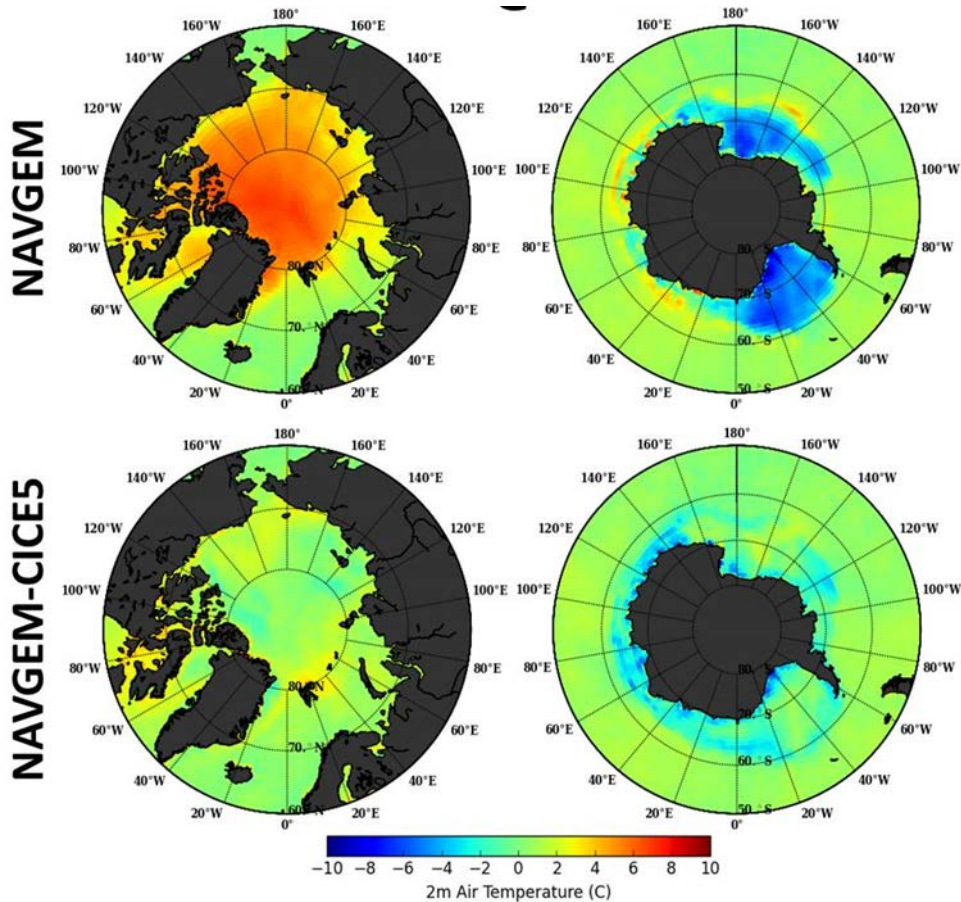


Fig. 3: 2-m Temperature bias (deg C) of 120-h forecasts for the month of May 2014 for the Arctic (left) and Antarctic (right) regions for stand-alone NAVGEM forecasts (top panels) and NAVGEM-CICE5 coupled forecasts (lower panels).

The tripole grid version of WW3 has been run on the DSRC with binary file input from HYCOM that includes water levels, 10-m wind speed, surface currents and ice concentration. [More specifically, these are 60-day computations on the "GLBa0.24" tripole grid (variable resolution from 5 km to 27 km) on DSRC machine "kilrain".] Comparison of the significant wave height for WW3 with (right panel) and without (left panel) input from HYCOM is shown in Fig. 4. The currents impact the wave model through 1) shifting energy in frequency space, 2) changing effective wind speed, and 3) refracting wave energy. Inclusion of the HYCOM forcing, while not resulting in dramatic changes, does have an impact, and it is encouraging that the runs are stable. James Chen (SAIC) has re-run this WW3 tripole case on the DSRC, calling WW3 from the ESMF/NUOPC driver.

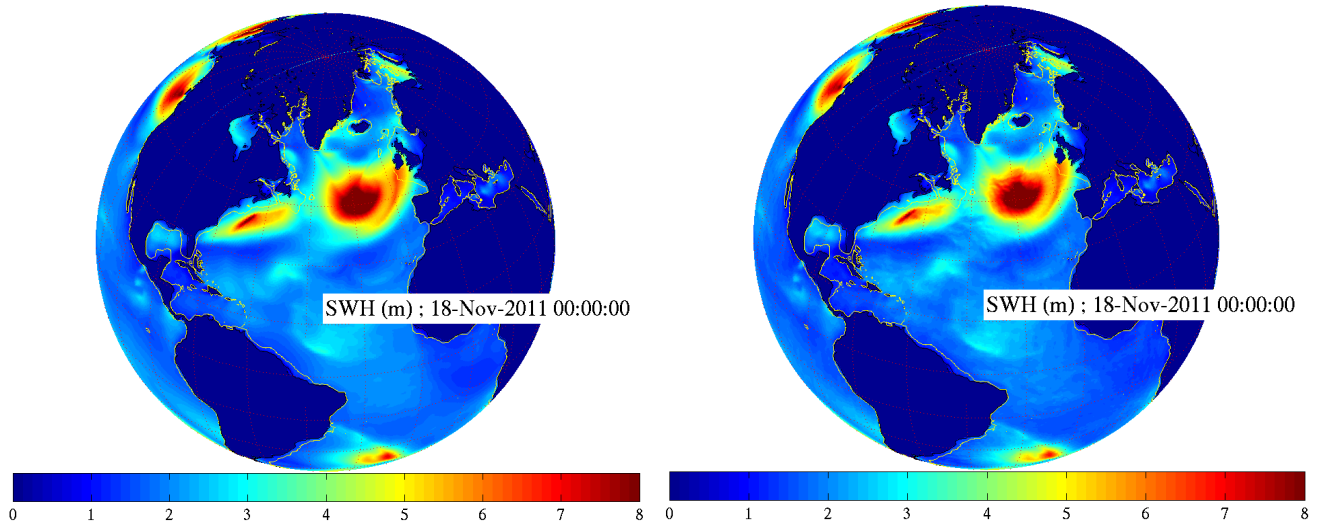


Fig. 4: Significant wave height (m) from WW3 forecasts without (left) and with (right) input from HYCOM. Forecasts valid at 00Z 18 NOV 2011.

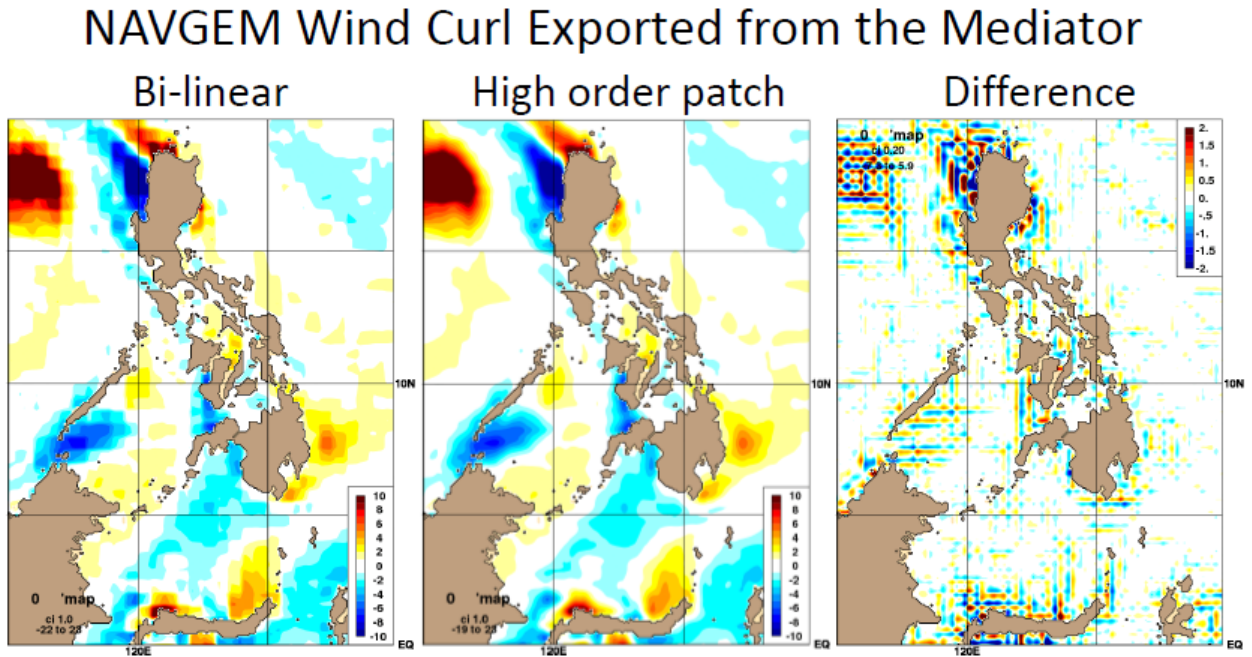


Fig. 5: Wind stress curl over the Philippines from NAVGEM passed through the mediator on the 0.08 deg HYCOM grid using bilinear interpolation (left), high order patch interpolation (middle) and the difference (right).

A thorough investigation of the interpolation techniques used within the ESPC mediator was performed by examining the interpolated fields passed between the component models. The original ESPC mediator was configured to use bi-linear interpolation for all atmospheric fields, both scalar and vector. However, it was determined that issues existed when interpolating from the relatively coarse atmospheric grid to the fine ocean/ice grid, especially for derivative fields - wind stress curl.

Figure 5 shows wind stress curl passed from the mediator to the ocean for the Philippines region using bilinear interpolation (left), high order patch interpolation (middle) and the difference (right). The bilinear interpolation generates noise on the fine ocean grid and is not appropriate for vector fields. The high order patch interpolation is consistent when compared to the interpolation used in uncoupled NAVGEM/HYCOM/CICE. The cost for higher order patch interpolation is not significantly higher than bilinear interpolation, so it has become the default interpolation technique used in the mediator.

IMPACT/APPLICATIONS

The future impact of this project is to provide the Naval operational environmental prediction system that is targeted for IOC in 2018.

RELATED PROJECTS

This work is part of a larger ESPC project. Collaboration with the 6.1 ONR sponsored Unified Physics for Extended Range Prediction DRI, 6.2 MJO Key to Extended Range Forecasts and 6.2 Consistent Momentum Balances for Surface Waves is acknowledged. Other 6.4 efforts in improving the current global atmosphere and ocean models will benefit the ESPC effort as well.